PRELIMINARY EXPERIMENT ON NEAR-FIELD SOUND PRESSURE MEASUREMENTS OF VIBRATING OBJECTS

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ABSTRACT

In this project, I conducted a preliminary near-field acoustic holography (NAH) experiment as part of the MUMT 618 project, focusing on validating the methods proposed in my previous work [1]. My main contribution was setting up and performing near-field sound pressure measurements using the available facilities at CAML and CIRMMT, leveraging a customized microphone array and excitation system. This experiment aimed to acquire real-world sound pressure data that could validate the NAH approaches I developed earlier.

Index Terms— One, two, three, four, five

1. INTRODUCTION

Near-field acoustic holography (NAH) is a widely used technique for identifying and visualizing sound sources in acoustics [2]. By analyzing the sound pressure data from a nearby microphone array (at the so-called hologram plane), NAH reconstructs actual source surface velocity fields, allowing for the identification of vibrating regions and providing insights into how complex sources radiate into the medium. See Fig. 1 for NAH general setup. In addition to its diagnostic capabilities [3], NAH offers practical advantages, particularly for delicate or lightweight objects such as musical instruments [4, 5, 6], as it avoids potential damage from accelerometers and the added mass of measuring equipment.

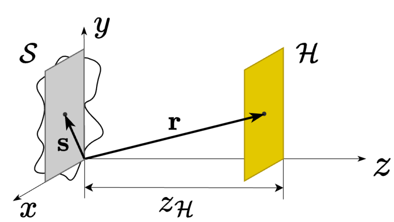

Figure 1: General setup for NAH. $\mathcal{S}$ and $\mathcal{H}$ represent actual source surface and hologram planes, respectively. $Z_{\mathcal{H}}$ is the distance between $\mathcal{S}$ and $\mathcal{H}$.

Predicting surface velocity from hologram sound pressure, which involves inverting the Kirchhoff-Helmholtz (KH) integral, is a highly ill-conditioned process due to capturing the evanescent waves emitted by the sound source in near-field, typically requires regularization [7]. Additionally, the problem is usually under-determined, meaning there are more surface points than measurements, leading to a non-unique solution subspace. The basic NAH problem addresses the scenario of stationary sound fields at a single frequency [8]. Subsequently, transient NAH techniques have been developed to reconstruct time-dependent pressure and visualize the sound field in both time and space domains, moving toward real-time industrial applications [9].

Numerous methods exist for NAH, with some of the most popular including Fourier-based NAH [2], plane or spherical wave expansions (such as the Helmholtz Least Squares (HELS) method [10], statistically optimized NAH [11]), and inverse numerical approaches (such as the inverse boundary element method [12, 13]). Another commonly used technique is the Equivalent Source Method (ESM), also referred to as the wave superposition method [8, 14, 15, 16]. It is grounded in the Huygens–Fresnel principle, which posits that every point on a wavefront acts as a secondary source of spherical wavelets. ESM models the sound emitted from a source surface using a layer of virtual monopole point sources positioned slightly inside the physical source, radiating into the free field [8]. The method is based on the fundamental idea that an arbitrary wave-field can be expressed as the superposition of waves radiated by a collection of point sources. The weights of the equivalent sources are estimated by minimizing the error between the measured pressure field and the pressure field obtained by propagating the equivalent sources. Recently, following the success of Deep Neural Networks (DNNs) in solving acoustic problems, DNNs have been employed for NAH. In [17, 18, 19, 20], NNs are typically employed to map hologram sound pressure to source velocity. For example, a part of my master thesis's work [1] was developing a complex-valued UNet-based convolutional neural network (CNN) (CV-KHCNN) for NAH [20], building on earlier frameworks [19, 17, 18]. We then proposed another two deep learning approaches to address NAH problem, which has not been published yet.

Due to the limited equipment available in my previous research group, conducting experiments was challenging. As a result, the approaches proposed in my thesis [1] were tested solely on simulation datasets generated using COMSOL Multiphysics. With the support of CAML and CIRMMT, I now have the opportunity to perform NAH measurements. Consequently, I decided to undertake a preliminary experiment on NAH as MUMT 618 project. Given the constraints of time and available equipment, the project focuses exclusively on near-field sound pressure measurements. The primary motivation for this project is to perform NAH measurements that can be used in the future to validate the approaches proposed in [1].

2. EXPERIMENT DESIGN

For the near-field sound pressure measurement, several key aspects must be considered: the measured object, the excitation method, the pressure measurement process, the measurement environment, and the configuration. Each of these aspects is elaborated upon below:

2.1. Measured objects

Three objects have been selected as case studies for this project: a drumhead (available in CAML), a rectangular wooden plate (randomly retrieved from discarded materials), and a violin (personally owned).

2.2. Excitation

For excitation, two types of signals can be utilized: signals containing all frequencies simultaneously (such as an impulse or white noise) or single-frequency signals. When using broadband signals, each channel of the time-aligned recorded data must be processed using a Fast Fourier Transform (FFT) to convert it into the frequency domain. The desired mode frequency can then be identified by selecting the peak in the frequency spectrum. For single-frequency signals, a preliminary measurement using a hammer test is required to determine the mode frequency of interest. This pre-measurement identifies the specific frequency to be used for subsequent measurements.

The hammer test is a widely used method for obtaining frequency responses, as it generates an impulse response (in NAH: [4, 5, 21]). However, in NAH measurements, it is crucial to avoid placing obstacles between the vibrating source and the sound pressure measurement points to minimize scattering effects. For violin measurements, when the hammer test is applied to the bridge, the excitation system is positioned between the vibrating surface and the measurement points, potentially introducing interference. As such, this setup may not always be ideal. A shaker is often preferred for NAH measurements as it provides a single-frequency excitation (in NAH: [22]). For violin measurements, the excitation can be applied to the back plate. However, care must be taken to ensure the excitation signal is strong enough for accurate measurements while preventing damage to the instrument. In this project, we have opted to use the hammer test.

2.3. Pressure measurement

A customized 64-channel rectangular condenser microphone array (featuring SENNHEISER KE 4-211-2 capsules) was used for pressure measurement at the hologram plane. The array consists of 8 units, each containing 8 microphones, assembled into a rectangular configuration specifically for this project. These units were originally designed for an arc-shaped microphone array configuration [1].

It is worth noting that the microphone heads are slightly misaligned, making it challenging to position them within a regular coordinate system. While this misalignment may not significantly impact the array's original design purpose for far-field measurements, it poses a challenge when predicting source velocity using pressure measurements obtained from this irregularly shaped array in the near field.

[1] https://www.music.mcgill.ca/caml/doku.php?id=equipment:ammar

2.4. Measurement Environment

The experiment was conducted in CAML, on the vibration isolation table, which is not an ideal environment. However, as this is a preliminary study primarily focused on setting up the experiment and evaluating its feasibility with the available equipment, we chose not to move to the hemi-anechoic room at CIRMMT. It is worth noting that, ideally, such experiments should be performed in an anechoic room.

2.5. Measurement configuration

A photo of the general experiment configuration is shown in Fig. 2. The microphone array audio signals are acquired using an RME Fireface 800, connected to the computer via RME MADIface USB, and recorded using the MATLAB toolbox *mxrtaudio* [2]. A customized hammer trigger system, designed by Mark Rau, is used to enable automatic triggering, ensuring consistent and repeatable measurements. The hammer signal is acquired using a National Instruments USB-4431 Signal Acquisition Board and recorded through MATLAB. The configurations of the drumhead, wooden plate and violin are shown in Fig. 3, 4 and 5 respectively. For the drumhead and wooden plate, the hammer excitation is applied from the back (see Fig. 3 and 4). For the violin, following standard practices in musical acoustics measurements, the excitation is applied at the bridge with a force parallel to the soundboard, on the soundpost side, as shown in Fig. 5. Ideally, the excitation would be applied on the bass bar side, but it is difficult to position the hammer trigger device on that side without removing the chinrest. Future improvements could involve moving the trigger point slightly closer to the microphone array side. Note that this setup may present challenges for NAH measurements, as discussed in Sec. 2.2. The boundary conditions are as follows: for the drumhead, it is clamped at the membrane edge (see Fig. 3); for the wooden plate, it is simply supported along the bottom edge and clamped at the two bottom corners (see Fig. 4 , right), with the other edges free. For the violin, it is supported by foam at the bottom, with the neck fixed, and the other areas free (see Fig. 5). Additionally, since the size of the violin is larger than the microphone array, we chose to use a 2-patch method, with the microphone meshes displayed in Fig. 5 (right). A similar approach was utilized for the measurement of Couchet harpsichord soundboard in [4].

3. RESULTS

The directly measured sound pressure signals from 64 channels are in the time domain, sampled at a rate of 48 000 Hz. It would be ideal to calibrate each microphone to ensure consistent power levels across all channels. While the noise floor appears relatively uniform, one microphone exhibits a significantly different signal compared to the others, making it challenging to equalize. Dropping this microphone would result in a 7×8 microphone configuration, reducing the spatial resolution. Therefore, I ultimately decided not to normalize the signals across channels, assuming that the microphones had already been calibrated.

The recorded signals are then processed using FFT to trasform into frequency domain. As an example, the processed drumhead signals are shown in Fig. 6. The peaks, clearly visible in the frequency spectrum shown in Fig. 6, correspond to the mode shapes.

[2] https://github.com/garyscavone/mxrtaudio

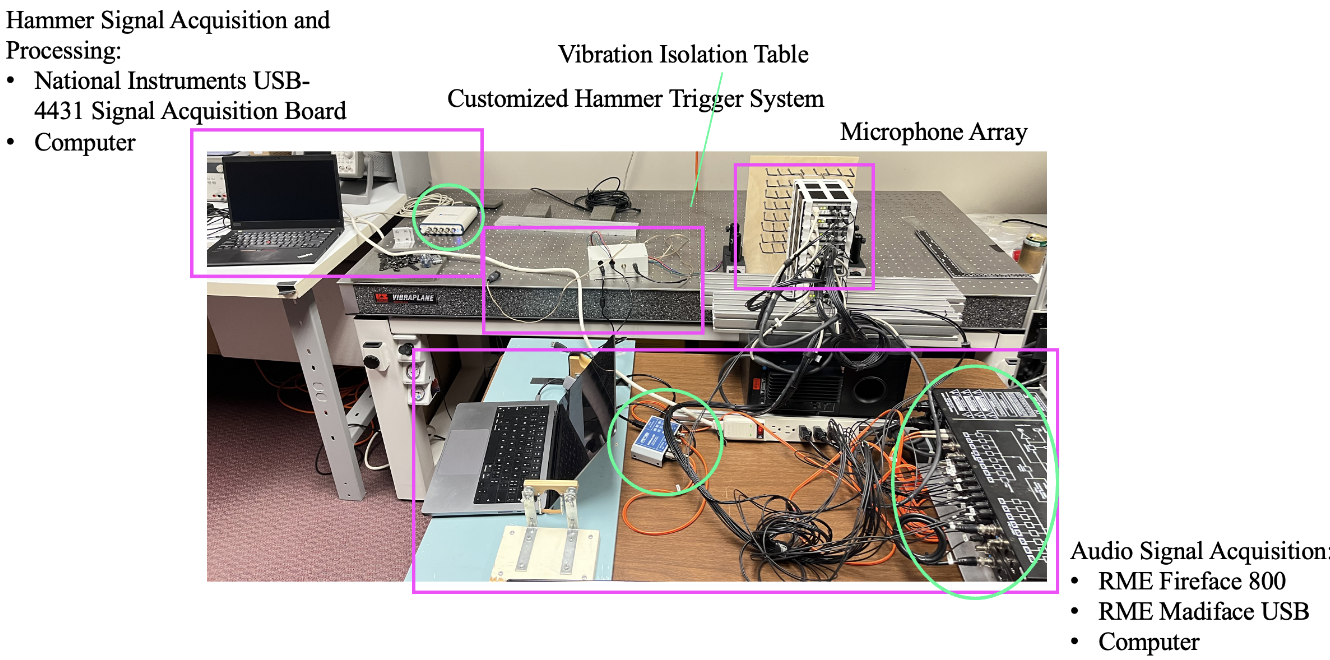

Figure 2: General experiment configuration.

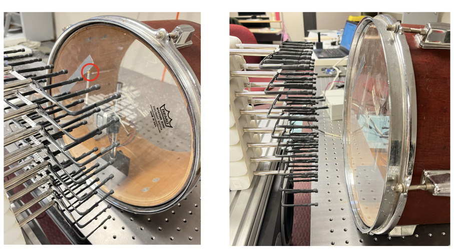

Figure 3: The experiment configuration of the drumhead, $z_{\mathcal{H}} = 7.7$ cm.

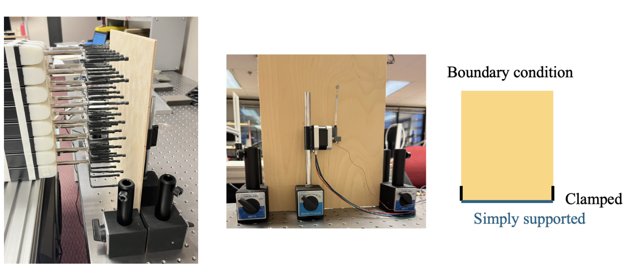

Figure 4: The experiment configuration of the wooden plate, $z_{\mathcal{H}} = 1.7$ cm.

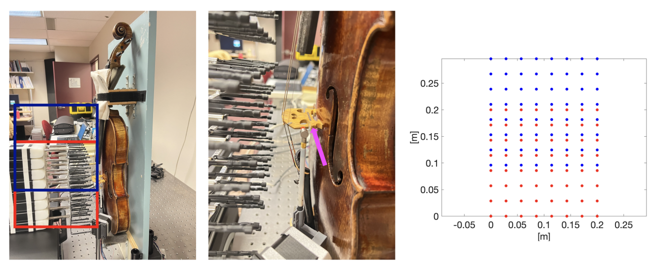

Figure 5: The experiment configuration of the violin, $z_{\mathcal{H}} = 6.8$ cm.

The measured near-field pressure signals (mode shapes) of the drumhead, wooden plate and violin are shown in Fig. 7, 8 and 9. Overall, it is clear that distinct patterns of the mode shapes are visible, indicating a reasonable experimental setup. To further compare the measurements with theory, an electronic speckle-pattern visualization of the drumhead mode shape from the literature [23] is presented in Fig. 10 for comparison. Our measured first mode at 101.44 Hz exhibits a monopole-like shape, followed by a dipole-like mode shape at 203.87 Hz and 218.64 Hz, aligning with Fig. 10. While it is challenging to distinguish the higher modes in our measurements, this comparison provides some confidence in the validity of our results. The mode shapes of the wooden plate are clearly visible in Fig. 8, although identifying the exact mode shapes would require surface velocity measurements. In contrast, for the case of the violin shown in Fig. 9, it is difficult to distinguish the mode shapes. All of the observed mode shapes appear to resemble monopole-like sound sources.

Since the drumhead exhibits known mode shapes, I applied the conventional Compressive-Equivalent Source Method (C-ESM) [22] to predict the actual source surface velocity. The results are

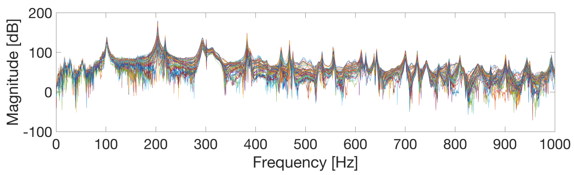

Figure 6: The frequency-domain drumhead sound pressure (64 channels) at the near-field.

shown in Fig. 11. The predicted surface velocity of the drumhead membrane reveals two point-source-like features. Although the measurement environment introduces a high noise floor that affects surface velocity prediction, the results show promise for future improvements in the experimental design, suggesting potential enhancements in measurement accuracy and reliability.

Remarks: It is important to ensure that the hammer signal strength is appropriate, as excessive force may cause the generated sound pressure to overload the microphone. Additionally, the hammer signal should be verified to contain only one distinct peak. Finally, careful attention must be given to selecting the optimal distance between the microphone array and the vibrating surface to achieve accurate measurements.

4. CONCLUSION

I conducted a preliminary experiment on near-field sound pressure measurements of vibrating objects, including a drumhead, a wooden plate, and a violin. The experiment was set up in CAML, a standard office environment, which may significantly impact the results. However, this is just the beginning. The goal is to understand how to configure the equipment and select appropriate measurement objects. The results show promise for further developing the experiment. Future improvements will focus on conducting measurements in an anechoic room to maintain a controlled acoustic environment. The ground truth for surface velocity will be accurately captured using a Laser Doppler Vibrometer (LDV). Additionally, foam could be attached to the microphone array to minimize reflections. Efforts will also be made to address the imprecise positioning of the microphone capsules, ensuring better spatial accuracy in the measurements.

5. ACKNOWLEDGMENT

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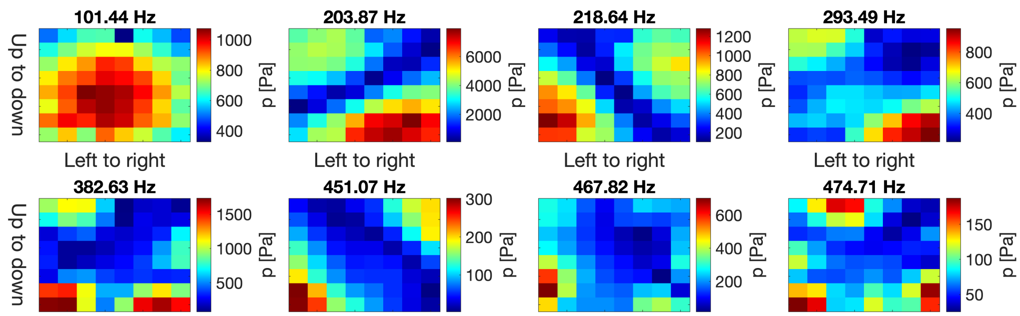

Figure 7: Measured mode shapes of the drumhead.

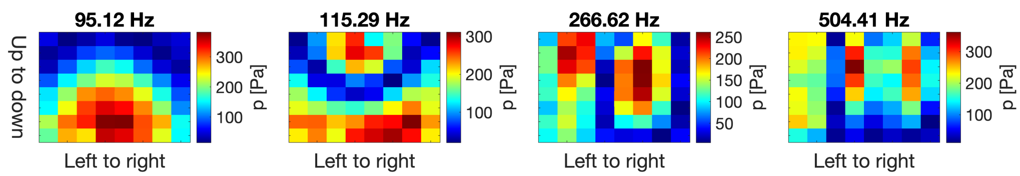

Figure 8: Measured mode shapes of the wooden plate.

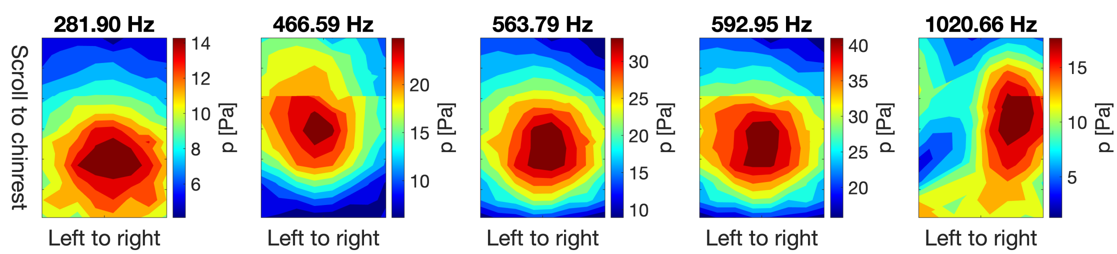

Figure 9: Measured mode shapes of the violin.

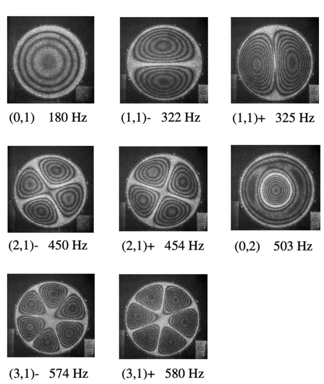

Figure 10: Electronic speckle-pattern images showing the first several modes of a "tuned" drum (Fig. 4 in [23]).

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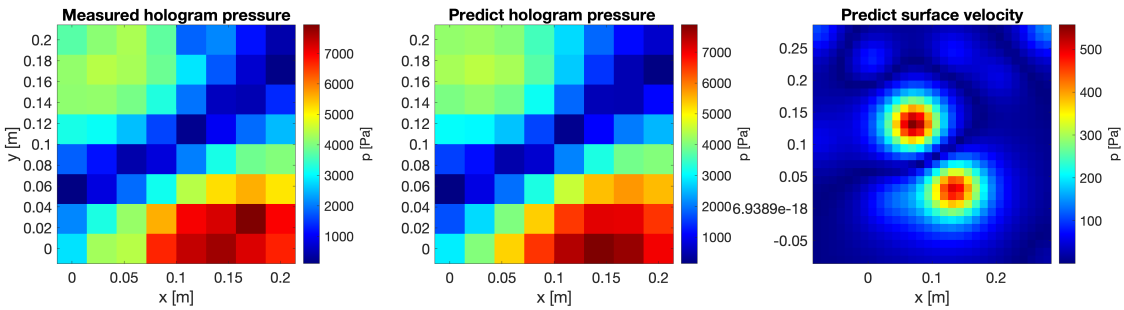

Figure 11: C-ESM results for the drumhead at 203.87 Hz. Left: Measured hologram pressure; Middle: Predicted hologram pressure from the estimated equivalent sources; Right: Predicted surface velocity of the drumhead membrane.

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